OPTIMUM BUOYANCY REQUIREMENTS FOR WEIGHT-LIMITED DEEP SUBMERSIBLES

by

PAUL A. PETERSON

Lieutenant, U.S.N.

S.B., United States Naval Academy
(1957)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF NAVAL ENGINEER

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DEGREE OF MASTER OF SCIENCE

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at the

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Paul A. Peterson

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Submitted to the Department of Naval Architecture and Marine Engineering on May 28, 1965, in partial fulfillment of the requirements for the degree of Naval Engineer and the degree of Master of Science in Naval Architecture and Marine Engineering.

ABSTRACT

Submersibles are limited in depth by the strength of the pressure hull. The pressure hull, in turn, is limited in strength by the properties of the material used in fabrication, construction techniques, and by the weight of material used in construction. Once the ballast weight has been taken up in hull weight, a limit is reached in depth. To go deeper with the same payload, the hull must be enlarged or size may be held constant, the hull strengthened and flotation material attached to support the extra weight. Either of these methods, enlarging the hull or adding flotation, increases size greatly as depth is increased.

This thesis is a study of total vehicle size versus depth for weight-limited deep submersibles with and without buoyancy material attached.

Thesis Supervisor: Philip Mandel

Title: Professor of Naval Architecture

ACKNOWLEDGMENTS

The author is indebted to Professor P. Mandel, Professor W. R. Porter, Cdr., U.S.N., and Professor J. H. Evans, without whose guidance and patience this thesis would not have become a reality.

The author also wishes to express his thanks to the crew of TRIESTE II, who put up with his unending questions during the summer of 1964, giving him his initiation into the real world of deep submersibles.

The hull weight studies described herein were done on the 7094 computer at the Massachusetts Institute of Technology Computation Center.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

I. DISCUSSION

A. Volume-Limited Submarines

1. Conventional submarines have operated routinely in the upper layers of the ocean for the better part of a century. These submarines, designed primarily as military vehicles, are large, providing the necessary internal volume required by men and equipment. Weight of hull and equipment is less than the sea water displaced, thus it is necessary that these vessels carry ballast to attain neutral buoyancy.

2. To design a submarine for maximum depth, it is necessary that the hull weight be increased. This can be accomplished with a volume-limited submarine with no increase in size by trading ballast weight for hull weight. The depth to which a volume-limited submarine can be designed with no increase in size is then, a function of the ballast it carried. Beyond that depth the weight of hull and equipment exceeds the weight of sea water displaced, and the vehicle becomes weight-limited requiring additional buoyant support to maintain neutral buoyancy.

B. Deep Submersibles

1. Oceanographers require small laboratories to carry them to the depths of the sea. The designer's problem in building submarines to satisfy the needs of oceanography is to build vehicles capable of carrying a scientifically useful payload to a scientifically interesting depth, usually the maximum depth possible. Submarines of a given size, limited in depth by hull weight and hull materials, have several avenues of approach by which their depth may be increased. First, vehicles may be made larger with payload fixed. Improved pressure hull materials may be used or flotation material may be attached to the vehicle to provide the lift necessary to restore neutral buoyancy. The first and last of these methods result in large craft which are less maneuverable, more complicated, and more expensive to build. This thesis examines and compares the penalties paid in achieving maximum depth by the methods just described utilizing various pressure hull materials.

II. PROCEDURE

A. General Approach

1. A number of assumptions are made concerning the family of vehicles to be considered, the structural materials available, the desired payload, the propulsion characteristics and the other features which will affect the buoyancy-weight balance. The assumptions are not necessarily optimum for the range of vehicles considered, but they represent an average of the features of TRIESTE II, ALUMINAUT, and ALVIN as they apply to the family of vehicles considered.

2. A computer program was developed to optimize hull weight for a given depth. The program is described in Appendix A. Using the computed results of hull weight versus depth as a base, the weight of payload, batteries, dropable ballast, main propulsion units, and "all other" variables was added. This resulted in a basic vehicle capable of proceeding to a given depth without the need of flotation material. At lesser depths additional ballast is required and at greater depths added lift is necessary.

3. Vehicles of various size were used in the computation of hull weight versus depth. Size was varied in two ways: by holding outside diameter constant while increasing length and by holding the length to diameter ratio constant. The results determine changes in size with an increase in depth for the two methods of increasing displacement.

4. Finally, flotation is considered as a means of hull support at increased depth. The addition of flotation necessitates an addition of the variables mentioned above, batteries, ballast, etc. This reduces the effect of the flotation material. Curves were constructed for syntactic foam, probably the best flotation material now available, and for materials of lower densities which might be developed in the not-too-distant future. These curves take into account the weight of additional equipment to arrive at a reduced flotation effectiveness. Entering the curves with the additional lift required by a basic vehicle at a given depth, one determines the volume of flotation material required, weight of flotation, and the weight of the added hardware necessitated by the additional displacement. The result of primary interest is the displacement of flotation to be added to the displacement of the basic vehicle. Total displacement is then plotted against depth for comparison of size with similar curves for the larger pressure hulls considered.

B. Assumptions

1. A family of cylindrical vehicles with hemispherical end caps is considered.

2. A basic vehicle with outside diameter of seven feet and L/D ratio of 2.0, where L is the length including the hemispherical ends, is considered. Hulls with eight-foot and 10-foot diameters, also with L/D ratios of 2.0, are considered for comparison as are vehicles of seven-foot diameter with L/D ratios of 2.5 and 3.0. Thus, size is varied in two ways; by holding L/D constant and by holding D constant.

3. Four materials are considered for construction as follows:

Material	Yield Strength	Modulus of Elasticity	Density
Steel	80,000 p.s.i.	30×10^6 p.s.i.	490 lb./ft.^{3}
Steel	150,000 p.s.i.	30×10^6 p.s.i.	490 lb./ft.^{3}
Titanium	120,000 p.s.i.	15×10^6 p.s.i.	281 lb./ft.^{3}
Aluminum	60,000 p.s.i.	10×10^6 p.s.i.	168 lb./ft.^{3}

Glass was also included for comparison in the computation of hull weights, using the same theory applicable to metals. This theory may, but probably does not give realistic values for the weight of glass hulls. The properties used for glass are as follows:

Glass	300,000 p.s.i.	14×10^6 p.s.i.	184 lb./ft.^{3}

The values of hull weight for glass are tabulated in Tables I - III but are not plotted.

4. Power requirements are based on a sustained speed of five knots for a period of ten hours. The auxiliary load is assumed to be 10 kilowatts.

5. Main propulsion power is assumed proportional to the product of displacement to the two-thirds power and the speed in knots cubed. Since the speed is fixed at five knots, power is proportional to displacement to the two-thirds power.

6. Silver-zinc batteries with the following properties are assumed for the power source.

Capacity 6.5 kilowatt hours/cubic foot
23.0 pounds/kilowatt hour(1)

7. Payload including complement and instruments is held constant at 2,000 lbs. for all vehicles.

8. Minimum volume requirement for payload and equipment was assumed to be 366 cu.ft. which is the internal volume of the seven-foot diameter, L/D = 2 pressure hull.

(1) Keays, K., "Parametric Study of Two Man Search and Work Submarines," General Dynamics/Electric Boat contract study, page 24.

9. Auxiliary buoyancy is assumed initially to be syntactic foam with a density of 44 lbs. per cubic foot. Buoyant materials with lesser densities of 0.50 (32.1lb. per cu.ft.) and 0.30 (21.33 per cu.ft.) are studied for comparison.

10. The remaining weights which do not fit into the categories of hull, batteries, or payload vary with a number of parameters. Some vary with displacement, some with depth, some with speed and some with external or internal surface area. It is not the purpose of this paper to analyze each of these weight groups, but estimates must be made in order to concentrate on the buoyancy requirements. It is assumed, therefore, that the following weight categories in addition to hull, battery and payload will be considered.

Main Propulsion units - function of displacement - 3% of displacement

Flotation material - function of buoyancy requirements and depth

Ballast - function of total displacement - 8% of displacement

All Other - for the purpose of this thesis a function of displacement - 8% of displacement[2].

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(2) Wenk, E., Jr., DeHart, R. C., Mandel, P., and Kissinger, R., Jr., "An Oceanographic Research Submarine of Aluminum for Operation to 15,000 Feet", Transactions R.I.N.A., Vol. 102, No. 4. Oct. 1960. Based on estimates made for ALUMINAUT, page 15.

C. Basic Vehicle Weights

1. A computer program was developed based on the class notes from course 13.15, M. I. T., by J. Harvey Evans. The program optimizes frame size and frame spacing to arrive at a least weight solution for a hull of a given size, constructed of a given material. The computer program is described in Appendix A. The results are tabulated in Tables I - V.

2. Figure VI is a graph of battery weight versus total displacement. For vehicles above 30,000 lbs., battery weight can be treated as a constant plus a percentage of the displacement over 30,000 lbs. with an error less than one-tenth of one percent of total hull displacement at all times. For a vehicle to which flotation material is to be added, the additional battery weight equals 1.4 per cent of the additional displacement.

3. Ballast, propulsion units, and "all other" also are functions of displacement and, like batteries, these weights may be treated as a constant which is part of the basic vehicle, plus a weight equal to a percentage of the displacement of the buoyant material added. Added weight due to an increase in displacement amounts to 20.4% of the added displacement.

4. Figures II - V are plots of weight versus depth and take into account hull weight, batteries, ballast, propulsion units, "all other", and payload. Weights plotted in Figures II - V are exclusive of any flotation material. Displacement is also plotted in Figures II - V for the differently configured vehicles. Comparison of displacement to weight yields the ballast or the added lift required for neutral buoyancy.

D. Buoyancy

1. The buoyancy of a vehicle is equal to the weight of salt water displaced. Flotation material must be added to a vehicle which weighs more than it displaces; ballast must be loaded aboard a vehicle which weighs less than its displacement.
2. The addition of flotation material necessitates an addition in the requirements for batteries, dropable ballast, main propulsion units, and "all other". Having linearized battery weight as a function of added displacement, all of the above items may be treated as a single weight addition proportional to the flotation material displacement.
3. The lift produced by flotation material is also a percentage of the flotation material displacement. The percentage may be treated as the effectiveness of the material. Syntactic foam, at 44 lbs. per cubic foot

is 31.3% effective. A material with a density with respect to sea water of 0.5 is 50% effective and one with a density of 0.3 is 70% effective.

4. The effectiveness of the flotation material is reduced by the additional weight described in paragraph 2 of this section. The reduced effectiveness is the flotation material effectiveness less the percentage of added weight. For the assumptions made in this study, the reduced effectiveness of syntactic foam is 10.9 (31.3 - 20.4); of the 0.5 density material it is 29.6; and of the 0.3 density material it is 49.6. Since this reduced effectiveness is the true indication of lift contributed to a basic vehicle, it can be seen that reducing the density from 0.687 to 0.5 increases the effective lift almost threefold. Flotation material displacement is reduced to one-third of the initial requirement and added batteries, dropable ballast, etc., is only one-third as much.

5. Figures VII - IX are graphs of flotation material characteristics and weight additions. Entering along the ordinate of the graph with the lift required by a basic vehicle at a given depth, the curves provide the following information:

Curve 1 - Lift applied to the basic vehicle

Curve 2 - Lift applied to additional batteries, ballast, etc.

Curve 3 - Total lift provided by the flotation material

Curve 4 - Dry weight of flotation material to be added

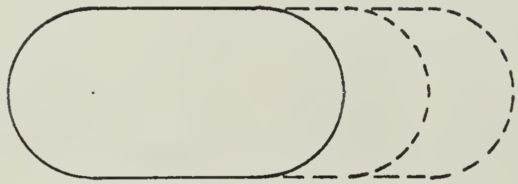
Curve 5 - Salt water displacement of flotation material to be added

These curves apply to any of the vehicles in the family of vehicles considered, provided that flotation material is to be added to provide additional lift.

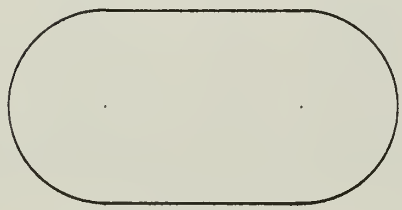
III. PRESENTATION OF RESULTS

Pressure Hull Sizes

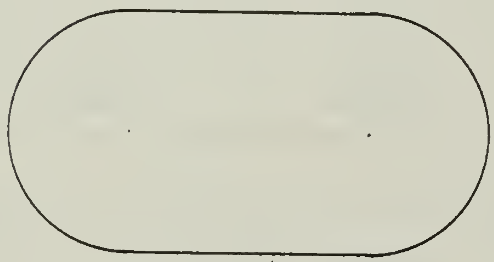
Figure I



D = 7', L/D = 2.0, 2.5, 3.0



D = 8', L/D = 2.0



D = 10', L/D = 2.0

Displacement of Hulls

Hull Diameter	L.O.A.	L/D	Displacement (Lbs. Salt Water)
7'	14'	2.0	28,650
	17.5	2.5	37,300
	21.0	3.0	45,950
8'	16.0	2.0	42,900
10'	20.0	2.0	83,500

Table I

Computed Cylinder Weights L/D = 1.5

	Collapse Depth			
D	3,400 ft.	10,200 ft.	17,000 ft.	34,000 ft.
Steel, HY-80				
7'		14,838 lbs.	23,800 lbs.	45,400 lbs.
8'	8,145	21,830	34,900	67,100
10'	15,600	41,600	66,800	127,400
Steel, HY-150				
7'		8,600	13,500	25,200
8'		12,600	19,700	37,122
10'		23,900	37,600	71,000
Titanium				
7'		6,120	9,460	17,800
8'	3,620	8,920	13,900	26,390
10'	6,760	17,000	26,600	50,500
Aluminum 60				
7'	2,560		10,600	20,500
8'	3,740	9,780	15,700	30,300
10'	7,080	18,600	24,900	58,400
Glass				
7'		2,300	3,400	5,500
8'		3,500	5,000	8,100
10'		7,100	10,000	15,400

Table II

Computed Weight of 2 Hemispherical End Caps

Collapse Depth

D	3,400 ft.	10,200 ft.	17,000 ft.	34,000 ft.

Steel, HY-80

7'	2,300 lbs.	7,300 lbs.	11,900 lbs.	22,700 lbs.
8'	3,700	10,900	17,800	33,900
10'	7,200	21,200	34,700	66,100

Steel, HY-150

7'	1,320	3,930	6,500	12,700
8'	1,980	5,870	9,700	18,900
10'	3,860	11,500	18,900	36,900

Titanium

7'	1,050	3,060	5,000	9,280
8'	1,560	4,550	7,400	13,900
10'	3,040	8,900	14,500	27,100

Aluminum 60

7'	1,020	3,030	5,000	9,700
8'	1,530	4,500	7,400	14,400
10'	3,000	8,800	14,500	28,100

Glass

7'	250	740	1,230	2,400
8'	370	1,100	1,840	3,634
10'	730	2,200	3,600	7,100

Table III

Computed Pressure Hull Weights L/D = 2.5

D	Collapse Depth 3,400 ft.	10,200 ft.	17,000 ft.	34,000 ft.
Steel, HY-80				
7'		22,140	35,700	68,100
8'	11,850	32,700	52,700	101,000
10'	22,800	62,800	101,500	193,500
Steel, HY-150				
7'		12,530	20,000	37,900
8'		18,470	29,400	56,000
10'		35,400	56,500	107,900
Titanium				
7'		9,380	14,460	27,080
8'	5,180	13,470	21,300	40,250
10'	9,800	25,900	41,100	77,600
Aluminum 60				
7'	3,580		15,600	30,200
8'	5,270	14,300	23,100	44,700
10'	10,080	27,400	44,400	86,500
Glass				
7'		3,040	4,630	7,900
8'		4,600	6,840	11,730
10'		9,300	13,600	22,500

Table IV

Computed Pressure Hull Weights L/D = 2.0

D	Collapse Depth 3,400 ft.	10,200 ft.	17,000 ft.	34,000 ft.
Steel, HY-80				
7'		17,200 lbs.	27,800 lbs.	52,300 lbs.
8'	9,100	25,400	41,100	78,700
10'	17,600	49,000	79,200	151,100
Steel, HY-150				
7'		9,700	15,500	29,500
8'		14,300	22,800	43,700
10'		27,400	44,000	84,200
Titanium				
7'		7,150	11,300	21,200
8'	4,000	10,500	16,700	31,400
10'	7,500	19,700	32,200	60,500
Aluminum 60				
7'	2,730		12,000	23,400
8'	4,100	11,000	18,100	34,600
10'	7,700	21,200	34,400	67,000

Table V

Computed Pressure Hull Weights L/D = 3.0

D	3,400 ft.	10,200 ft.	17,000 ft.	34,000 ft.
Steel, HY-80				
7'		27,100 lbs.	43,700 lbs.	81,900 lbs.
8'	14,500	40,000	64,400	123,500
10'	28,000	76,800	123,700	236,100
Steel, HY-150				
7'		15,400	24,500	46,300
8'		22,700	35,900	68,500
10'		43,300	69,100	131,500
Titanium				
7'		11,200	17,600	33,000
8'	6,500	16,600	26,300	49,500
10'	12,200	32,000	50,500	95,500
Aluminum				
7'	4,400		19,100	37,100
8'	6,700	17,500	28,800	54,800
10'	12,400	33,600	54,300	105,900

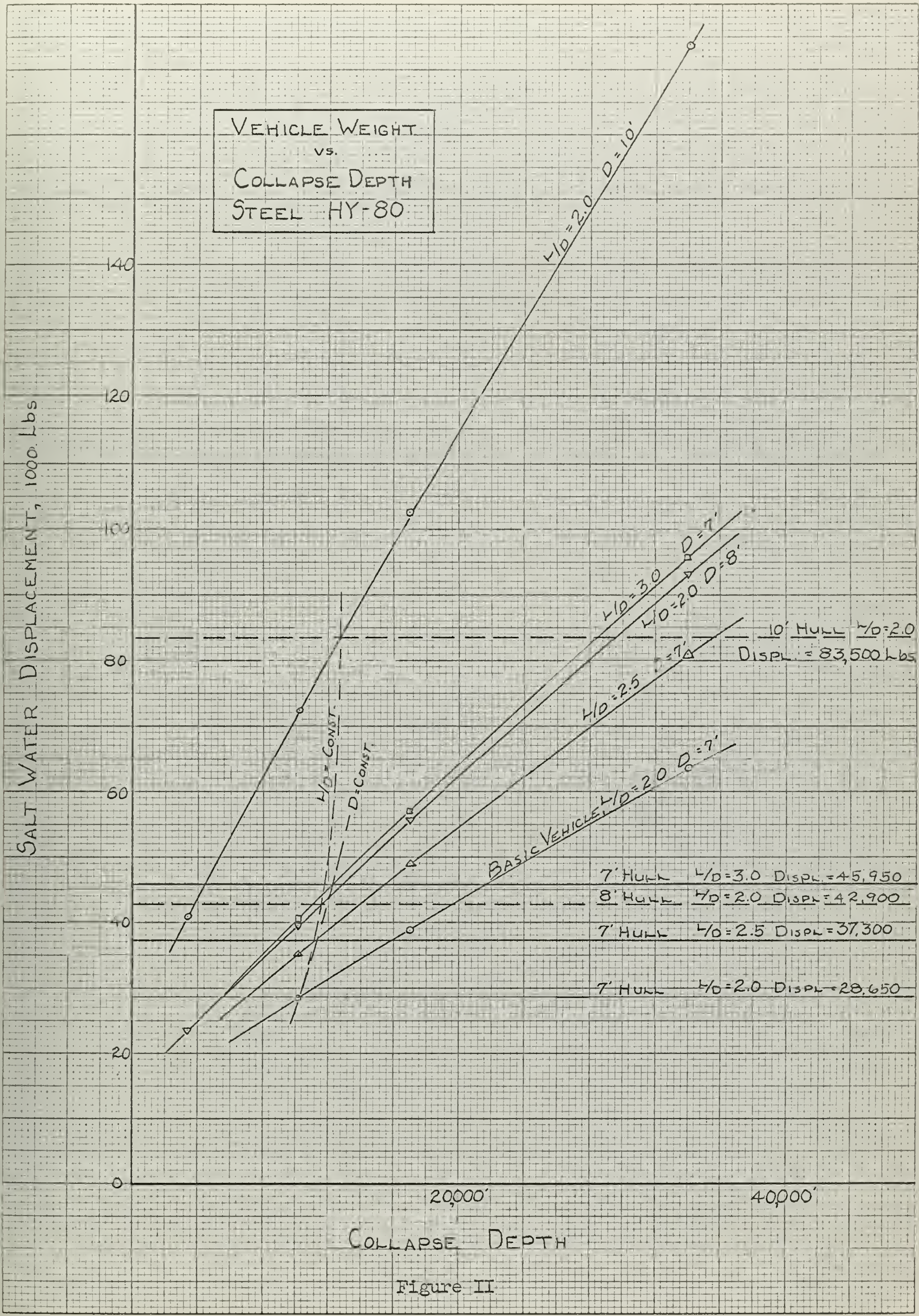
Table VI

Weights Added to Bare Hulls to Arrive at Basic Vehicle Weights

(Figures II-V)

Diameter	7'	7'	7'
L/D	2.0	2.5	3.0
Battery Wt. (Figure VI)	3,300	3,550	3,750
Ballast, Etc. (19% x Displ.)	5,450	7,100	8,740
Payload	2,000	2,000	2,000
Total	10,750	12,650	14,450

	8'	10'
L/D	2.0	2.0
Battery Wt.	3,600	4,300
Ballast, Etc.	8,150	15,900
Payload	2,000	2,000
Total	13,750	22,200



VEHICLE WEIGHT
vs.
COLLAPSE DEPTH
STEEL HY-80
SALT WATER DISPLACEMENT, 1000 Lbs
COLLAPSE DEPTH
0
20
40
60
80
100
120
140
20,000'
40,000'
L/D=2.0 D=10'
L/D=3.0 D=7'
L/D=2.0 D=8'
L/D=2.5 D=7'
BASIC VEHICLE L/D=2.0 D=7'
L/D=CONST.
D=CONST.
10' HULL L/D=2.0
DISPL. = 83,500 Lbs
7' HULL L/D=3.0 DISPL.=45,950
8' HULL L/D=2.0 DISPL.=42,900
7' HULL L/D=2.5 DISPL.=37,300
7' HULL L/D=2.0 DISPL.=28,650

Figure II

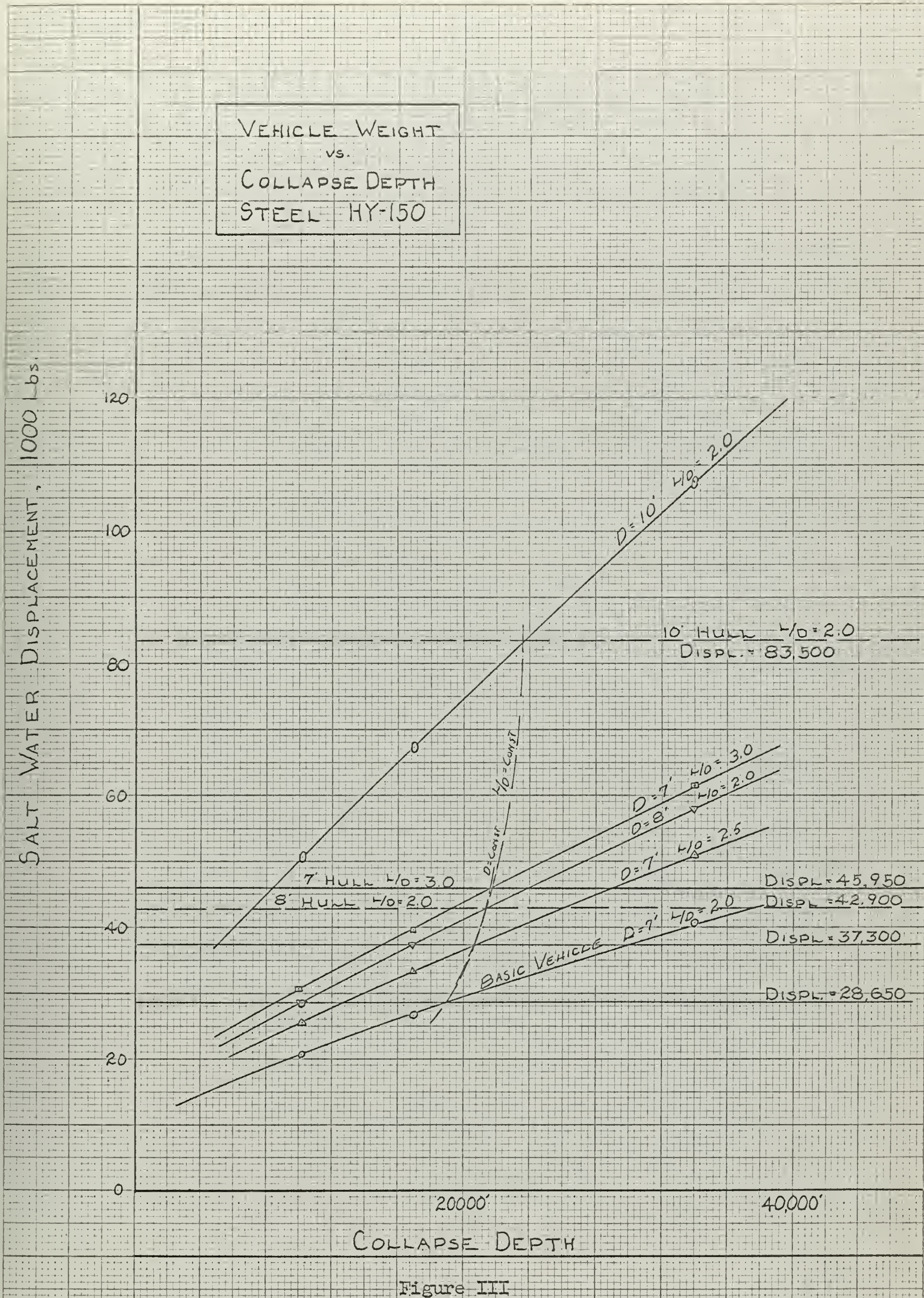

VEHICLE WEIGHT
vs.
COLLAPSE DEPTH
STEEL HY-150
SALT WATER DISPLACEMENT, 1000 Lbs.
120
100
80
60
40
20
0
20000'
40,000'
COLLAPSE DEPTH
D=10' L/D=2.0
10' HULL L/D=2.0
DISPL.=83,500
L/D=CONST
D=CONST
D=7' L/D=3.0
D=8' L/D=2.0
D=7' L/D=2.5
7' HULL L/D=3.0
8' HULL L/D=2.0
DISPL.=45,950
DISPL.=42,900
DISPL.=37,300
DISPL.=28,650
BASIC VEHICLE D=7' L/D=2.0

Figure III

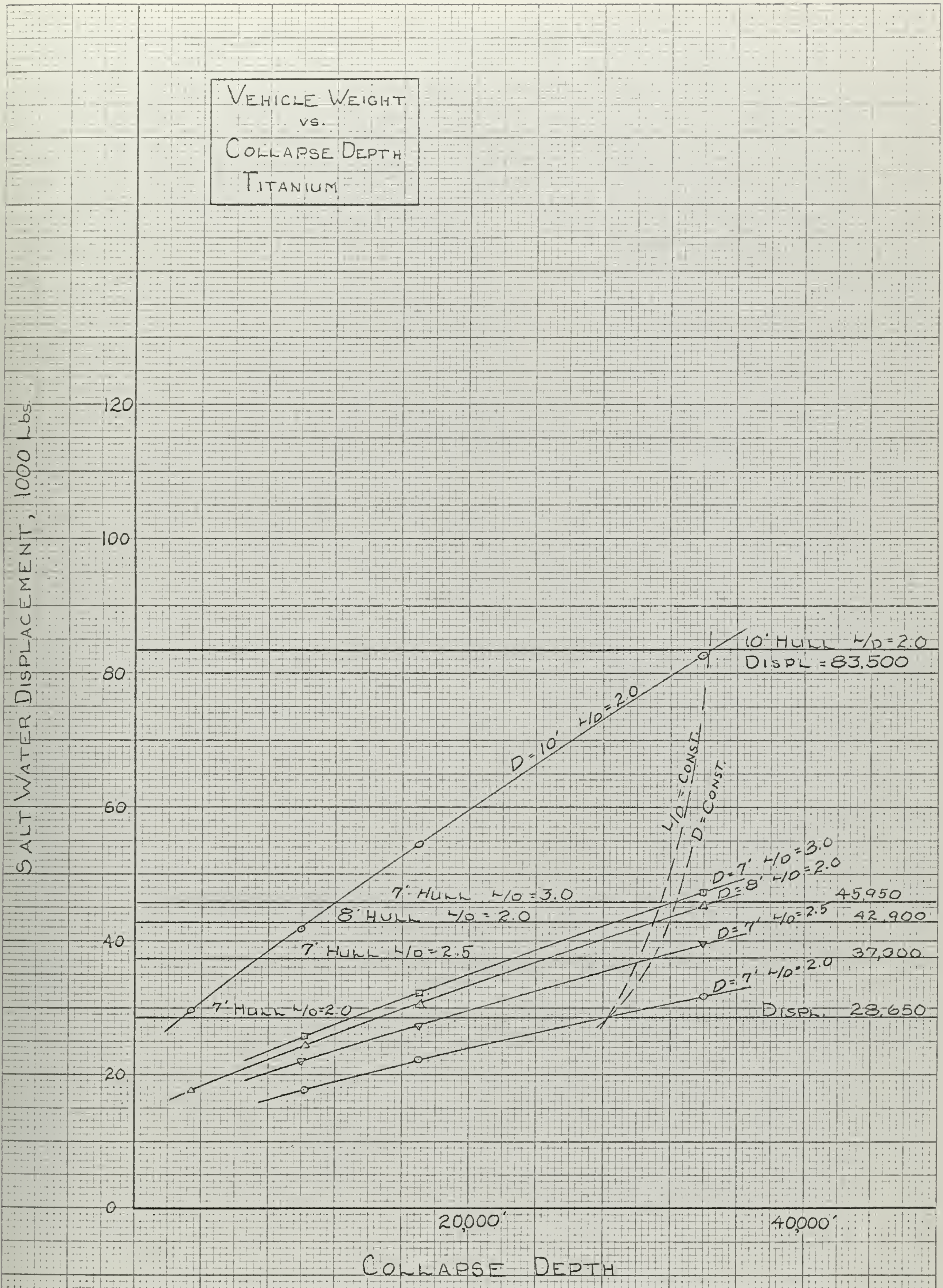
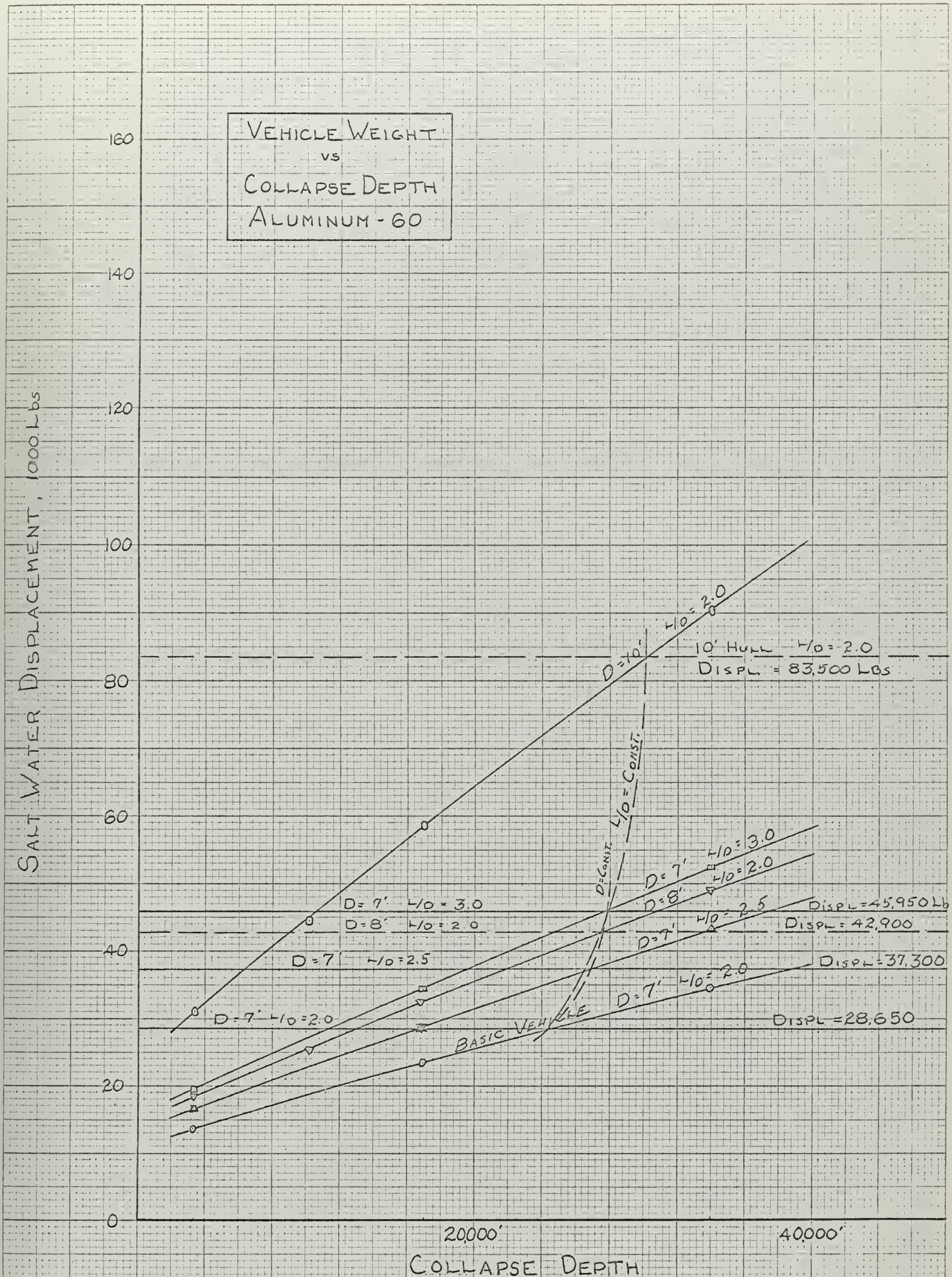


Figure IV

quares to the Inch



VEHICLE WEIGHT
VS
COLLAPSE DEPTH
ALUMINUM - 60
SALT WATER DISPLACEMENT, 1000 LBS
160
140
120
100
80
60
40
20
0
20,000'
40,000'
COLLAPSE DEPTH
D = 10'
L/D = 2.0
10' HULL L/D = 2.0
DISPL = 83,500 LBS
L/D = CONST.
D = CONST.
D = 7' L/D = 3.0
D = 8' L/D = 2.0
D = 7' L/D = 2.5
D = 7' L/D = 2.0
DISPL = 45,950 LB
DISPL = 42,900
DISPL = 37,300
DISPL = 28,650
BASIC VEHICLE

Figure V

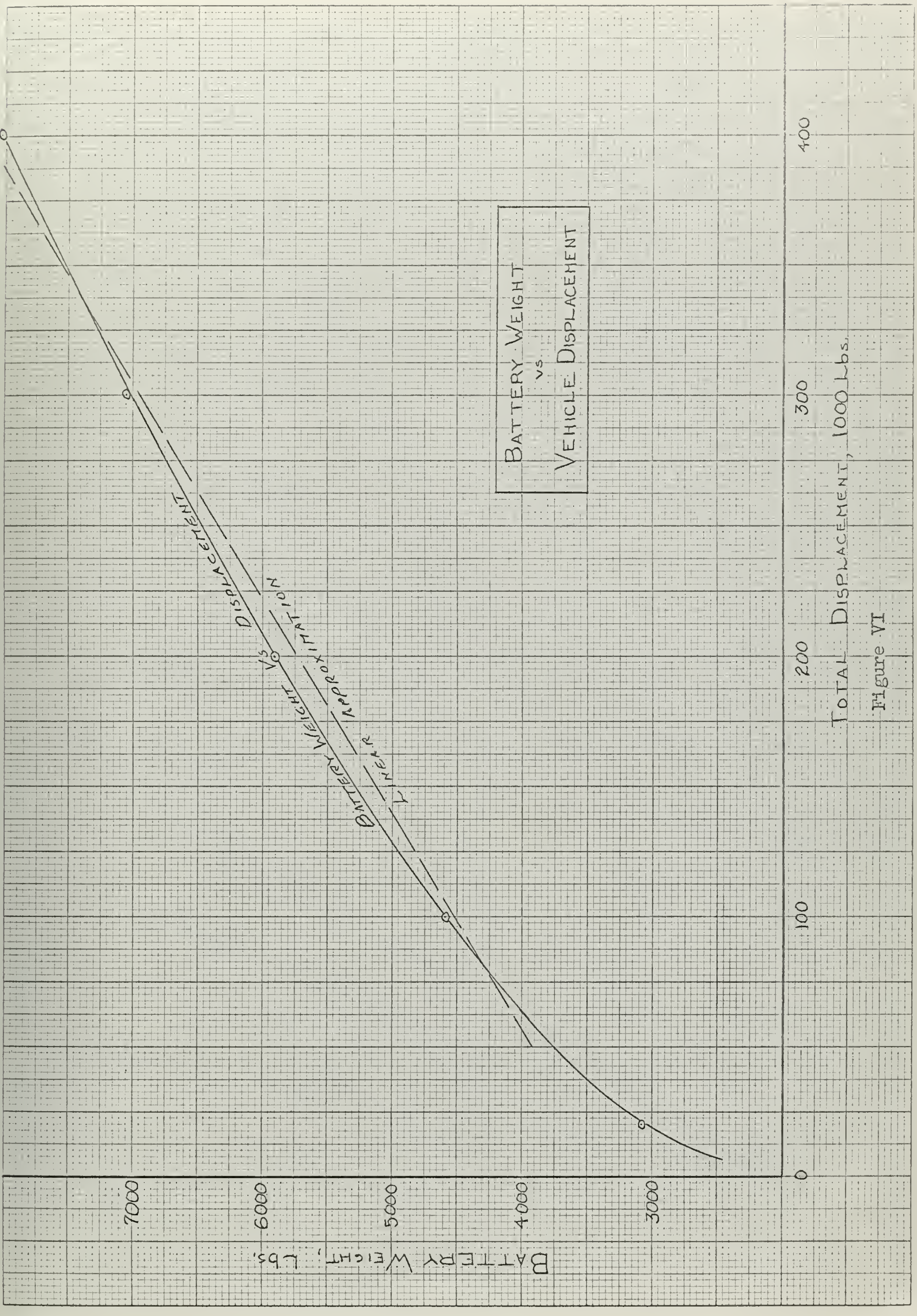

BATTERY WEIGHT vs VEHICLE DISPLACEMENT
BATTERY WEIGHT VS DISPLACEMENT
LINEAR APPROXIMATION
TOTAL DISPLACEMENT, 1000 Lbs.
BATTERY WEIGHT, Lbs.
0
100
200
300
400
3000
4000
5000
6000
7000

Figure VI

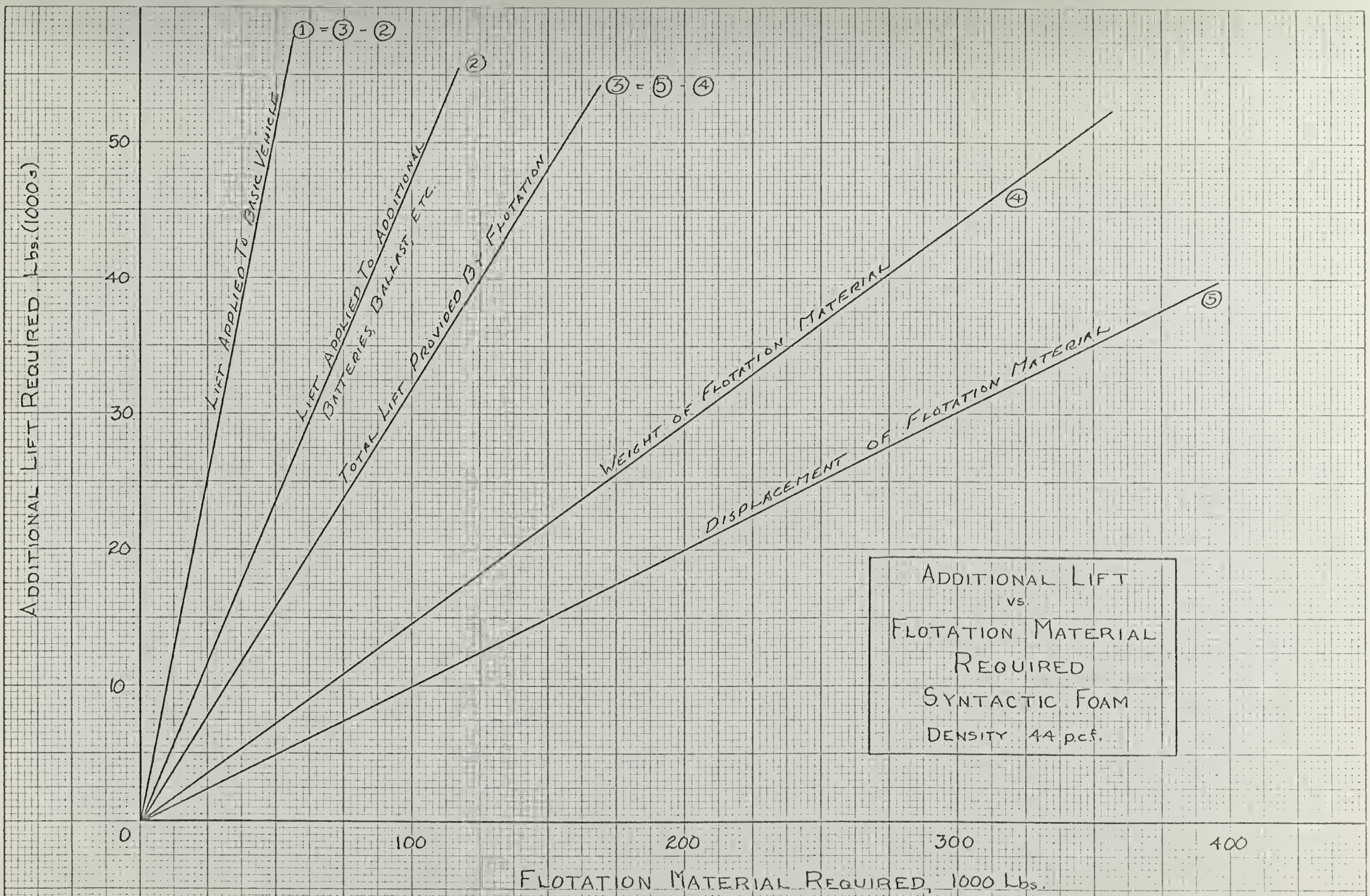
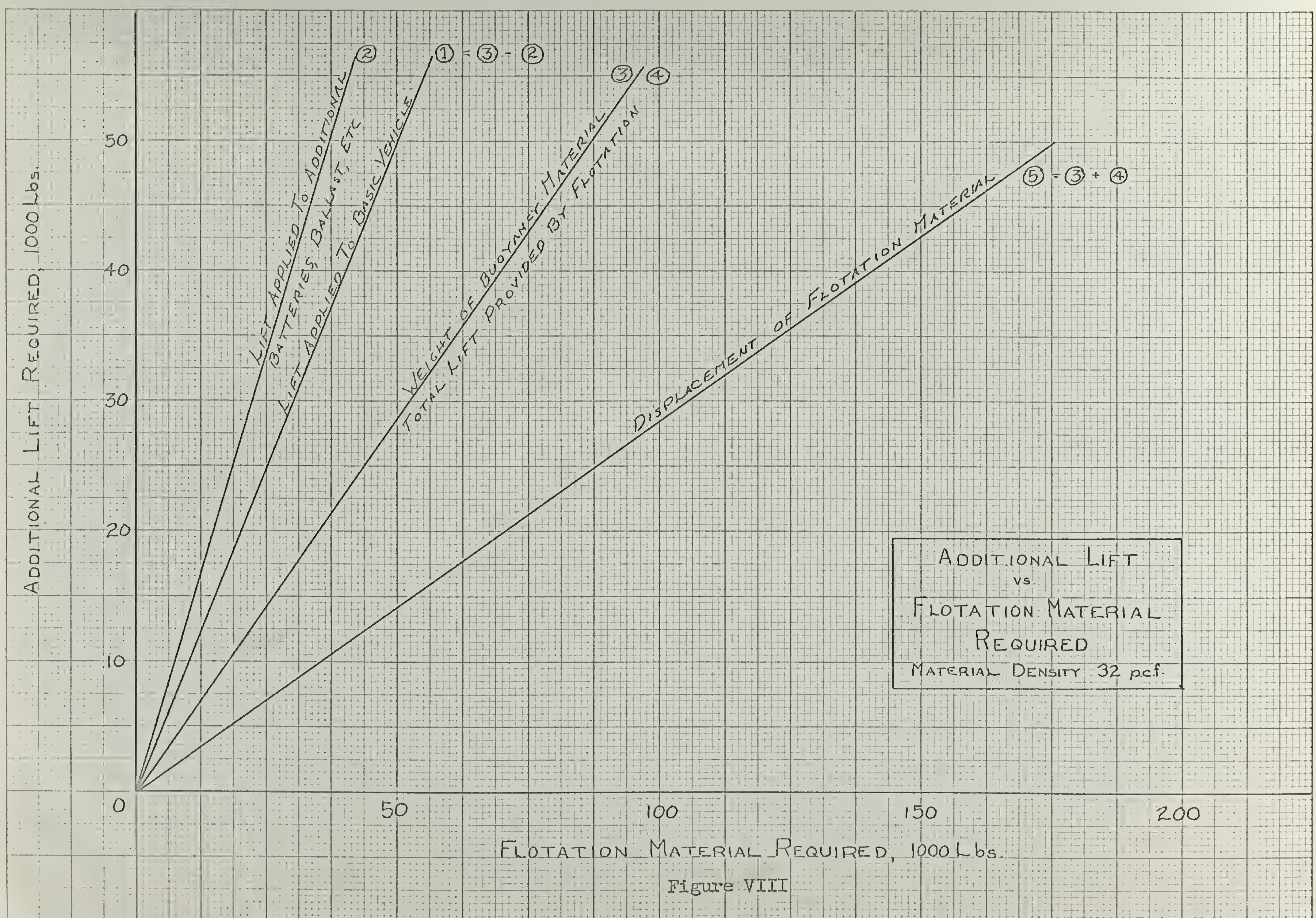

Additional Lift Required, Lbs. (1000s)
Flotation Material Required, 1000 Lbs.
0
10
20
30
40
50
100
200
300
400
Lift Applied To Basic Vehicle
① = ③ - ②
Lift Applied To Additional Batteries, Ballast, Etc.
②
Total Lift Provided By Flotation
③ = ⑤ - ④
Weight of Flotation Material
④
Displacement of Flotation Material
⑤
Additional Lift
vs.
Flotation Material Required
Syntactic Foam
Density 44 p.c.f.

Figure VII



② Lift Applied To Additional Batteries, Ballast, Etc
① = ③ - ② Lift Applied To Basic Vehicle
③ Total Lift Provided By Flotation
④ Weight Of Buoyancy Material
⑤ = ③ + ④ Displacement Of Flotation Material
Additional Lift vs. Flotation Material Required
Material Density 32 p.c.f.
Additional Lift Required, 1000 Lbs.
0
10
20
30
40
50
100
150
200
Flotation Material Required, 1000 Lbs.

Figure VIII

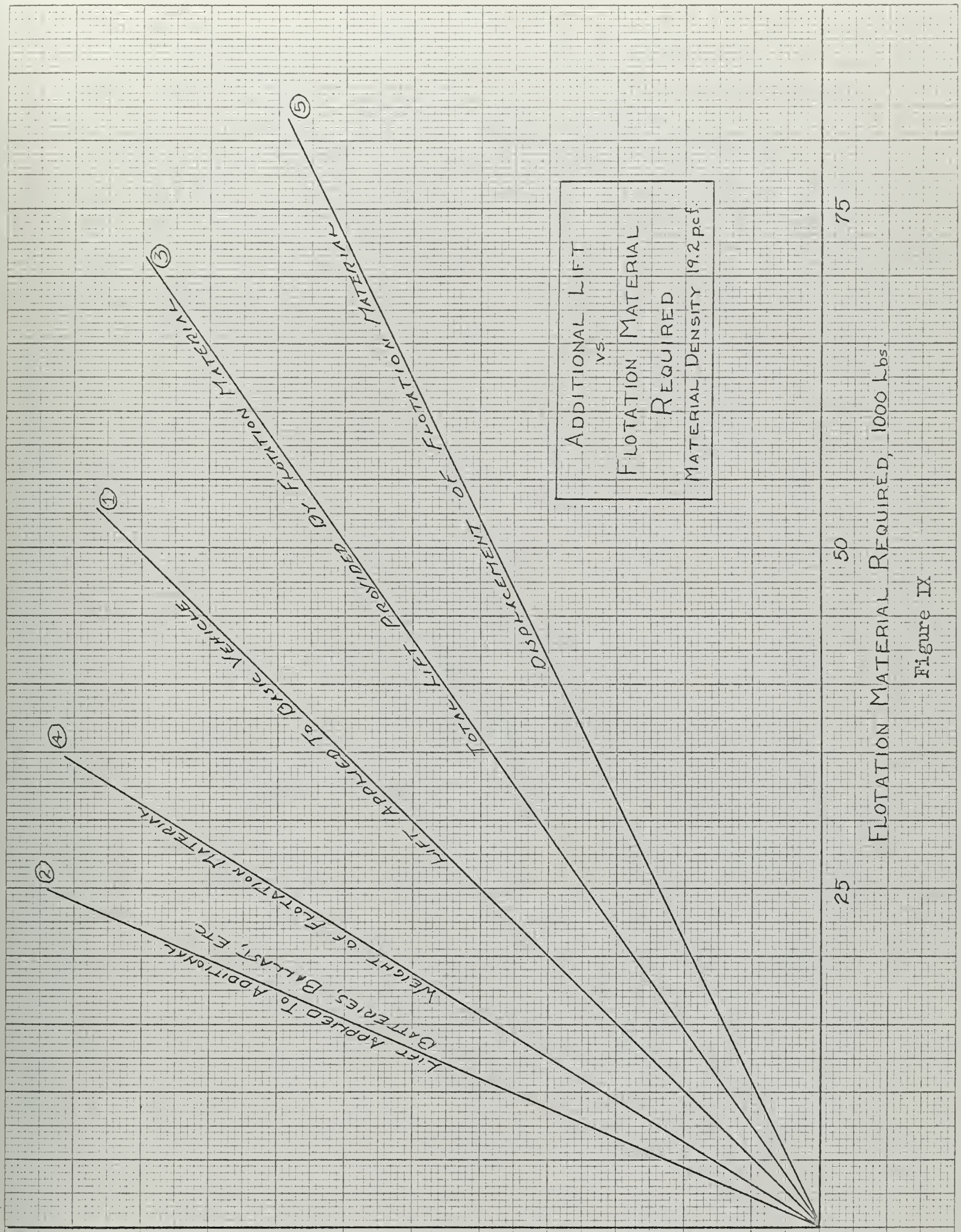

Additional Lift vs. Flotation Material Required
Material Density 19.2 p.c.f.
① Lift Applied to Basic Vehicle
② Lift Applied to Additional Batteries, Ballast, Etc.
③ Total Lift Provided by Flotation Material
④ Weight of Flotation Material
⑤ Displacement of Flotation Material
Additional Lift Required, 1000 Lbs.
Flotation Material Required, 1000 Lbs.
0
25
50
75
10
20
30
40
50

Figure IX

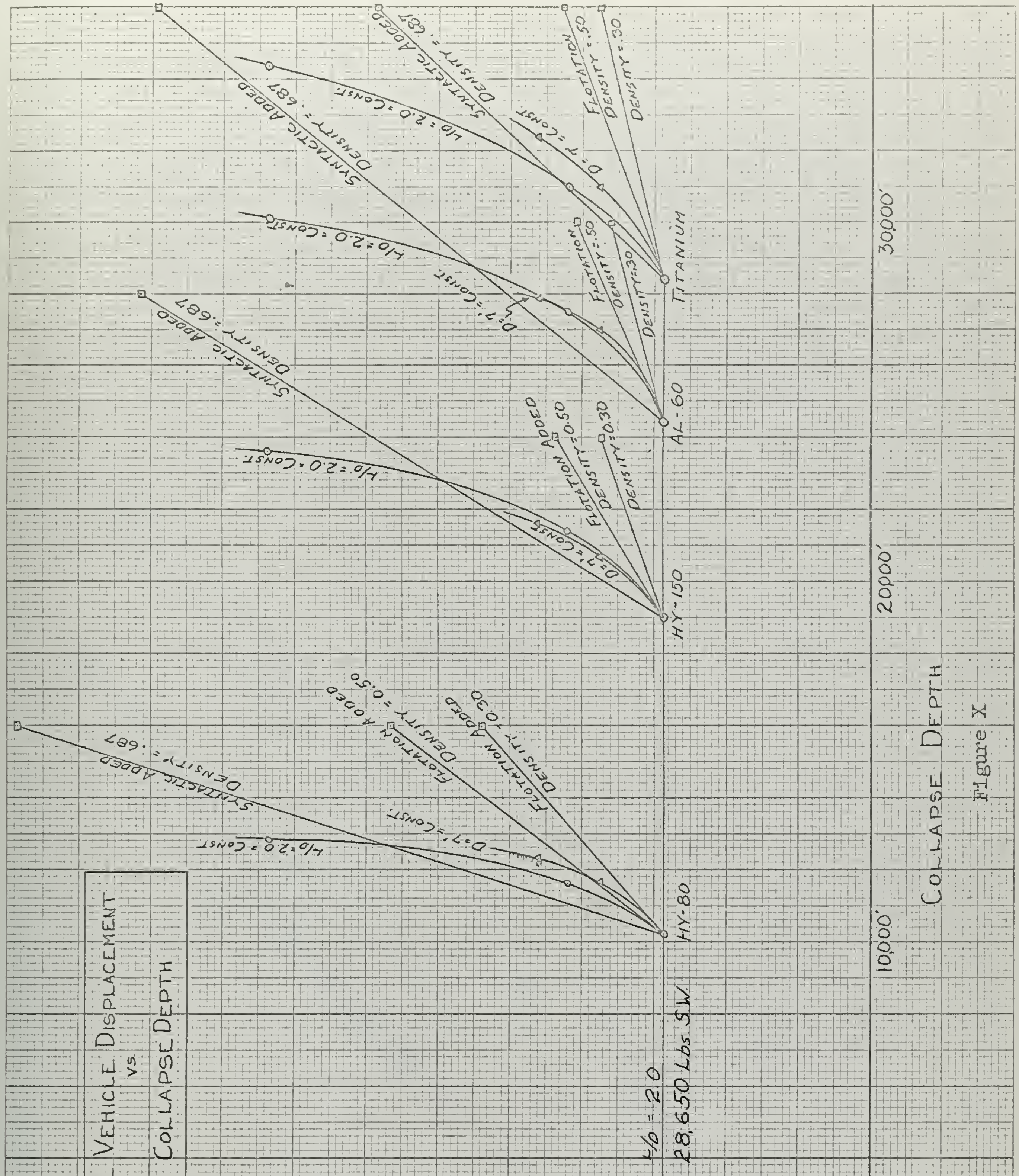
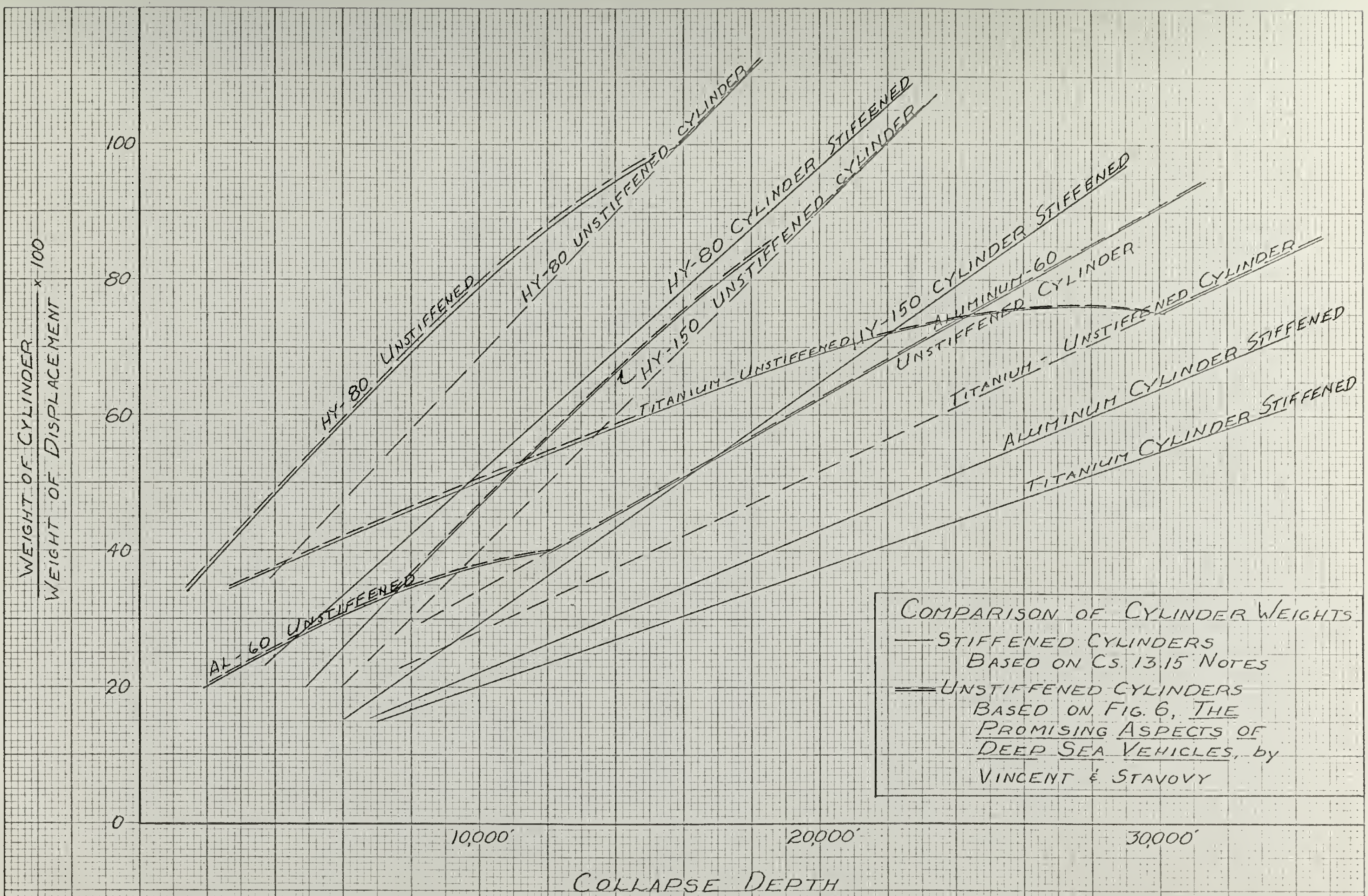

Total Vehicle Displacement
vs.
Collapse Depth
Vehicle Displacement, 1000 Lbs.
Collapse Depth
0
20
40
60
80
100
10,000'
20,000'
30,000'
D = 7' L/D = 2.0
Displ. = 28,650 Lbs. S.W.
HY-80
HY-150
AL-60
Titanium
Syntactic Added
Density = .687
Flotation Added
Density = 0.50
Density = 0.30
Flotation = .50
Density = .30
L/D = 2.0 = Const.
D = 7' = Const.

Figure X



WEIGHT OF CYLINDER / WEIGHT OF DISPLACEMENT x 100
0
20
40
60
80
100
10,000'
20,000'
30,000'
COLLAPSE DEPTH
HY-80 UNSTIFFENED
HY-80 UNSTIFFENED CYLINDER
HY-80 CYLINDER STIFFENED
HY-150 UNSTIFFENED CYLINDER
HY-150 CYLINDER STIFFENED
TITANIUM-UNSTIFFENED
ALUMINUM-60 UNSTIFFENED CYLINDER
TITANIUM-UNSTIFFENED CYLINDER
ALUMINUM CYLINDER STIFFENED
TITANIUM CYLINDER STIFFENED
AL-60 UNSTIFFENED
COMPARISON OF CYLINDER WEIGHTS
STIFFENED CYLINDERS BASED ON CS. 13.15 NOTES
UNSTIFFENED CYLINDERS BASED ON FIG. 6, THE PROMISING ASPECTS OF DEEP SEA VEHICLES, by VINCENT & STAVOVY

Figure XI

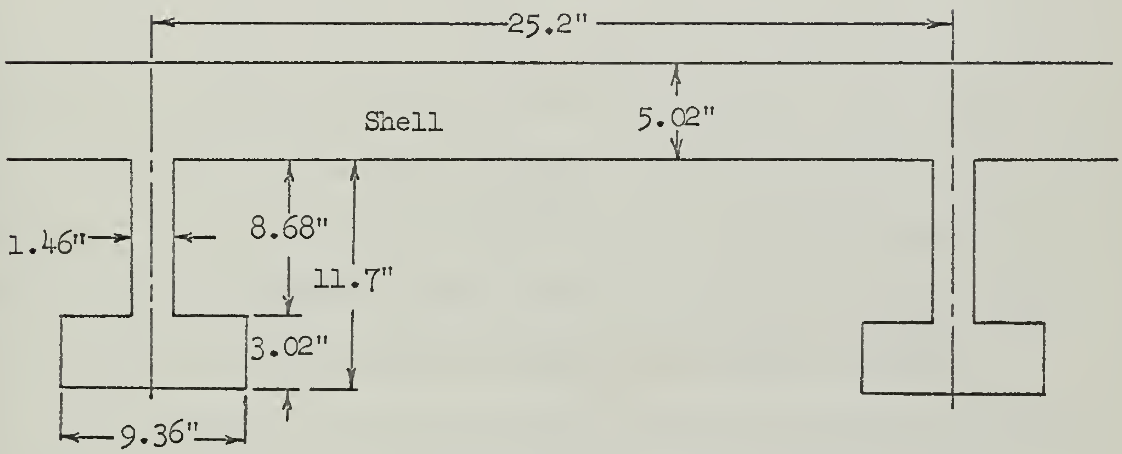
Figure XII

Sample Computer Solution

Material - Aluminum 60

Collapse Depth - 17,000 feet

Hull Diameter - 7'



IV. CONCLUSIONS AND RECOMMENDATIONS

A. Figure X displays the results required by section I of this thesis. Overall vehicle size is plotted against depth for hulls constructed of four different materials. The effect of increasing depth by changing hull size or by adding flotation material with pressure hull size constant is compared with the following results. Increasing hull size by varying vehicle length provides greater depth than building a larger vehicle with L/D constant for HY-80 and Titanium. For aluminum the opposite is true and for HY-150 both methods have equal effect. Therefore, the results with respect to a preferred method of increasing size are inconclusive, one method having nearly the same effect as the other. However, the addition of flotation material is to be preferred over changing vehicle size by either method for all but HY-80, assuming syntactic foam is the material used. For depth increases greater than about 5,000 feet, a smaller vehicle results if flotation material is added. And, of course, the cost of a given volume of flotation material will be much less than the cost of increasing hull size by an equal amount.

Recommendation: Deep submergence pressure hulls should be built large enough to satisfy minimum volume requirements. If added lift is necessary, it should be provided by flotation material.

B. The effect of improving the characteristics of flotation materials is graphically demonstrated in Figure X. If a flotation material could be produced with a density of 0.50, there would be no question about the preferred method of increasing depth.

Recommendation: As flotation material of lower density is developed, its use should be considered in the design of deep submersibles. Costs will be cut and smaller, less complex deep submersibles will result.

C. Although the results concerning a preferred method of changing vehicle size were inconclusive, it can be said that there is probably an optimum hull configuration. With the computer program developed, one could arrive at hull proportions for a least weight vehicle with a given displacement. At first glance it might appear that this would always result in a sphere, but with conventional framing or sandwich hull construction, this probably will not be the case. The program can also be used to determine optimum frame configuration, and it appears to be a very promising tool in evaluating current design practices as they apply to vehicles designed for greater depths.

Recommendation: The computer program described in Appendix A should be used to continue the study of hull configuration started in this paper and it could be used as well for a study of the parameters of submarine design and their interaction on one another.

D. Figure XI is a graphic illustration of the results obtained by using the methods outlined in the notes from course 13.15 and from earlier calculations based on unstiffened cylinder construction. Some difference

exists between the weight of unstiffened cylinders and the weight of the stiffened cylinder as predicted by the program in Appendix A. It is natural that a difference exist, but in some cases the unstiffened cylinder is limited to a depth 38% less than that of a stiffened cylinder of equal weight. This large difference is difficult to explain and it may be an indication that the notes on which the computer program is based may give incorrect collapse depths when considering deep submersibles, or, that the computer program contains some flaw. However, the program was tested using as inputs data from relatively shallow-depth submersibles, and it duplicated almost exactly the calculations which resulted when those vessels were designed.

Recommendation: The computer program, probably the most valuable by-product of this thesis, should first be checked once again to ensure that the formulae have been translated into computer language properly, and then the output should be compared with experimental results to determine:

1. the validity of the theory with respect to conventional steel construction,
2. the applicability to other metals, and
3. the application of the theory to vessels with t/D ratios approaching 0.1.

Having checked the program and its general applicability, it will be possible to determine the necessity of modifying the basic theory for metals other than steel or, more probably, for deep submergence vehicles with very thick shells.

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APPENDIX A

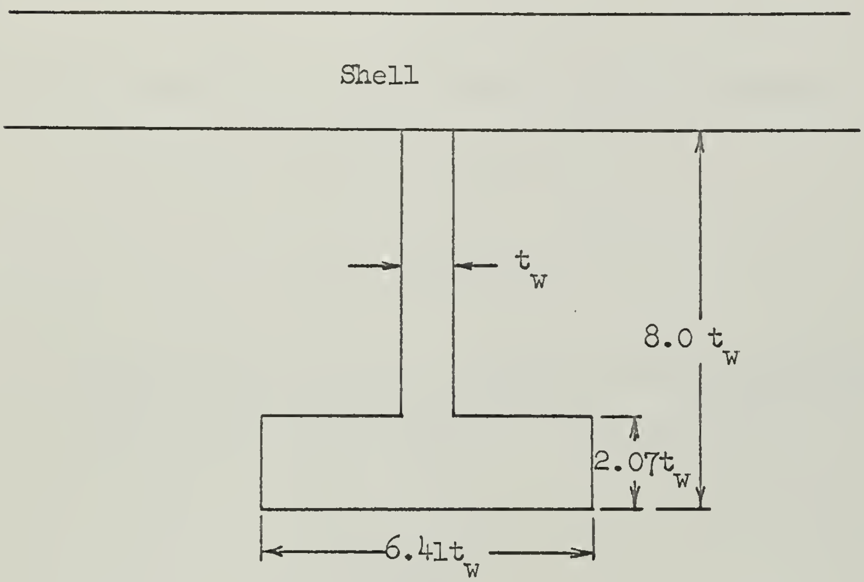
Computer Design Program to Optimize Submarine Hull Weight, based on class notes of Course 13.15, M. I. T., by J. Harvey Evans, Professor of Naval Architecture.

1. Background

   a. Failure of a stiffened shell occurs in one of three modes. The first occurs if the shell buckles between the frames while the frames retain their circularity. This is referred to as elastic or plastic instability. The second mode of failure involves yielding of the shell. In this mode the shell remains circular but the yield strength of the material is exceeded. The third mode of failure occurs when the shell and frames fail together and this is known as general instability. Ideally, for optimizing strength with least weight, a shell should fail in all three modes simultaneously. This program optimizes three parameters, shell thickness, frame area, and frame spacing in an attempt to find the least weight solution.

   b. In such a solution it would be ideal to optimize the dimensions of the frame as well as the other parameters mentioned, but this would have introduced another degree of complexity to an already complex analysis. Instead,

a frame typical of those presently used in submarine construction was selected as a parent and all frames are scaled from the parent member. The cross section of the parent member is shown in Figure A-1 below. All dimensions are with respect to 't_w', web thickness.



c. Having selected a parent frame member, it is only necessary to settle on the length of cylinder between bulkheads and the mean cylinder diameter in order to apply the formulae presented in the set of notes referenced above. The general method of approach outlined

is that of selecting a set of scantlings and checking their applicability. An understanding of the paper is necessary for a full understanding of the program and its capabilities. However, lack of such understanding will not prevent successful use of the program.

d. The program is based on the solution of six equations. These are:

1. Hoop stress formula which predicts a pressure at which shell yield occurs.

$$Pcr = 2(t/D)\ \sigma_y$$

This formula is used to determine shell thickness for a contemplated design. Shell thickness,

$$t = \frac{Pcr \times D}{2\sigma_y}$$

Experiments indicate that the predicted thickness may be reduced in some cases by as much as 20%. The computer program, however, completes two solutions, at predicted 't' and at 95% of 't' but a minor modification to the program allows 't' to be reduced to any given percentage of the value predicted by the hoop stress formula, or it allows

't' to be reduced in increments until a least weight solution is found which satisfies all other criteria but ignores the hoop stress prediction.

2. Formula 92a modified predicts plastic instability failure.

$$P_{cr} = \frac{\frac{2t}{D_m}\sigma_y}{1 + H\frac{0.85 - B}{1 + \beta}} \times \frac{1}{1 + 0.148(\lambda^2 - \epsilon)^2}$$

The critical pressure it predicts must be equal to or greater than collapse depth pressure. (see page 42 for a list of symbols and their meanings.)

3. Wenk's formula predicts collapse pressure based on the circumferential stress at the shell mid-thickness midway between frames.

$$P_{cr} = \frac{2t\sigma_y}{D} \times \frac{1}{\sqrt{F^2 - \frac{F}{2} + \frac{1}{4}}}$$

4. Lunchick predicts "yield pressure" based on a three hinge failure mechanism.

$$P_y = \frac{2t\sigma_y}{D} \times \frac{1}{\sqrt{X^2 - XZ + Z^2}}$$

This formula is normally within 3 - 5% of the collapse pressure predicted by Wenk.

5. Bryant has taken a collapse prediction by Kendrick and put it into a useful form. This formula is based on the number of complete circumferential waves formed by the plating and frames buckling as a unit. It is solved, normally for 2, 3, or 4 waves and the first critical mode of failure (i.e., the one for which the critical load is smallest) is the value sought.

$$P_{cr} = \frac{2Et}{D_m} \times \frac{m^4}{\left(n^2 + \frac{m^2}{4} - 1\right)\left(n^2 + m^2\right)^2} + \frac{8(n^2 - 1)}{D_m^{\,3} L_1} EI_1$$

Formulae 2, 3, 4 and three variations of 5, predict critical pressures. It is necessary to solve these formulae and then select that answer which is lowest as the critical one in the case under consideration.

6. The last formula used predicts the stress in the frame flange due to the combined effects of total load including shear and bending due to out of roundness. This formula is based on the critical pressures predicted by Bryant's formula; thus, it is also solved three times in the program.

$$\sigma_{max} = \frac{P_1 R}{A_b} b \left[\frac{1 + \frac{0.85\beta}{B}}{1 + \beta}\right] + \frac{E(c)}{R_m^2}(n^2 - 1)\ \delta\left(\frac{P_1}{P_{cr} - P_1}\right)$$

The highest values predicted by this formula must not exceed the yield strength of the material. Thus, the highest value is selected by the program as the critical value.

e. The program solves for shell thickness using the hoop stress formula and then computes six solutions for critical pressure. The lowest of the six is termed the critical pressure for solution of the problem. Then three solutions of maximum stress are made, and the highest of these is selected as the critical stress. At this point the program computes the amount by which critical pressure must be changed to agree with collapse pressure, and the amount by which the highest stress must be altered so it does not exceed yield strength of the material. If the program can be made to alter frame size and frame spacing until these values agree; critical pressure with collapse pressure, and maximum stress with yield stress, then for a given shell thickness, a least weight solution will be possible.

f. The solution is found by solving the problem with frame area incremented a unit amount and with frame spacing incremented a unit amount. These two solutions yield changes in the critical values of pressure and stress; that is, they

give the partial differentials of pressure and stress with changes in frame area and frame spacing. It is then a simple matter to assume that linearization is possible and solve two equations in two unknowns for the number of unit changes to be made in frame area, A, and frame spacing, SP.

$$\frac{\partial P}{\partial A} dA + \frac{\partial P}{\partial SP} dSP = (P_{collapse} - P_{crit})$$

$$\frac{\partial S}{\partial A} dA + \frac{\partial S}{\partial SP} dSP = (S_{yield} - S_{crit})$$

Solving for the two unknowns, dA and dSP, the original estimate of frame area and frame spacing can be changed. The problem is solved again with the new values of frame area and frame spacing and if the critical pressure is within a given percentage (the program specifies 4% on the safe side) and if the critical stress is also safe and within a set tolerance (these tolerances can be changed if a higher degree of accuracy is desired), the program will compute weight of compartment including shell and frames. (One word of warning. In order to ensure a satisfactory solution in all cases, it was necessary to make frame spacing continuous. Therefore, the number of frames, equal to compartment length over frame spacing may not be a whole number. It will be necessary to select the next higher number of frames to ensure a safe solution with a slightly higher weight than that computed.)

g. If, at the end of the first iteration, the values of predicted collapse pressure and predicted stress are not within tolerance, the program will continue to cycle through the series of calculations improving the solution until it is within tolerance. The program then increments shell thickness to 95% of its predicted value and solves the problem again. The weight determined is compared with the weight determined with the original value of 't' and the "least weight" is printed before the problem goes on to the next set of data.

<u>LIST OF SYMBOLS</u>

Some of the symbols in the following list refer to variables which are used to simplify the basic formulae. When such variables do not have explicit definitions, reference is made to a formula number, figure number, or page number, where the symbol is used in the notes by Professor Evans.

A	Cross sectional frame area
A_b	Area of one frame plus shell under the web
b	Web thickness of the ring frame
B	Page 18
c	Formula 31
D	Outside diameter of hull
D_m	Diameter of hull to mid-shell
E	Young's Modulus
F	Page 31
H	Figure 8
I_1	Moment of inertia of a T section
L_1	Frame Spacing
m	$3.14\ D \div 2L$ (rounded off to the nearest whole number)
n	2, 3, or 4 - no. of lobes for the three modes of failure by general instability
P	Predicted collapse pressure
P_{cr}	Pressure at which yield occurs

P_{crit}	Lowest collapse pressure of the 6 pressures calculated
P_y	Yield pressure - same as P_{cr}
P_1	Pressure at collapse depth
R_m	Radius of hull to mid-shell
S_{crit}	Highest stress of the three computed
SP	Frame spacing
t	Shell thickness
x	Page 34
z	Page 34
β	Page 18
ϵ	Page 9
λ	Slenderness ratio - Figure 4
YS	Yield stress

2. Input

a. Input consists of the length and mean diameter of the cylinder under consideration, the characteristics of the material to be used in construction, including yield strength, Young's modulus and density of the material, the collapse depth, allowable out-of-roundness of the hull, and the best estimate available of frame area and frame spacing.

Inputs	Units	Definition
A	in^2	Area of frame
CD	feet	Collapse depth
CL	inches	Compartment length
D	inches	Mean diameter of hull
Delta	inches	Allowable out-of-roundness
Dens	lb/in^3	Density of material
E	p.s.i.	Young's modulus
SP	inches	Frame spacing
SY	p.s.i.	Yield strength

(Delta, allowable out-of-roundness of the hull, should normally be limited to one-half inch or half the thickness of the shell. For heavy shell plating this may be increased, but for shell plating less than one-inch thick Delta will be altered by the program to one-half the thickness of the shell plating.)

b. All input for a single problem is placed on one card in the following form:

```
------ ---------- ---------- ------ ------ ------ ------ ---- ----
1 A    7   SY     17   E     27 D   33 CD  39 CL  45Dens 51SD 55Delta
```

The numbers indicate the card space number at which each item should start. Sample input follows:

```
70.---60000.----30000000.-360.--400.-540.---.2875-30.-.50-
```

The sample input indicates the following:

Frame area	70 sq.in.
Yield Strength	60,000 p.s.i.
Young's Modulus	30×10^6 p.s.i.
Mean diameter of hull	360 inches
Collapse depth	4,000 feet
Compartment length	540 inches
Density of material	.2875 lb. per $in.^3$
Frame spacing	30 inches
Allowable out-of-roundness	0.50 inches

An input deck ready for the computer will consist of the following cards:

Meaning	Space	Number
	1	7
Identity	*	M3999-3504,FMS,DEBUG, 1, 1, 500, 75 Peterson
Execute	*	XEQ
Binary	*	BINARY (or FORTRAN)
Comment	C	Peterson (this card included only if a fortran deck is used)
		First binary or fortran card of program
		-
		-
		-
		Last card of program
		END
	*	DATA
		First data card

```
      DIMENSION PCAM(6),PCW(6),PCL(6),PCB1(6),PCB2(6),PCB3(6
     1),SMK1(6),SMK2(6),SMK3(6),P(10),S(4),W(40),PDIFS(10)
     2,SDIFS(10)
 10   READ 1340,A,SY,E,D,CD,CL,DENS,SP,DELTA
      PCD=CD*64./144.
      PRINT 1010,SY
      PRINT 1040,CD
      PRINT 1090,PCD
      T=CD*64.*D*0.5/(144.*SY)
      IF(T-0.25)20,30,30
 20   T=0.25
 30   IF(T-1.0)40,50,50
 40   DELTA=T/2.
 50   CONTINUE
      SY=0.98*SY
      CD=1.02*CD
      PRINT 1020,E
      PRINT 1030,D
      PRINT 1050,CL
      PRINT 1060,DENS
      PRINT 1080,DELTA
      PCD=1.02*PCD
      LR=1
 15   L=1
      LO=1
      LP=1
      NP=1
      NQ=1
C     PRELIMINARY CALCULATIONS
 60   FN=CL/SP+1.
      IF(A) 64,64,65
 64   PRINT 1390,A
      GO TO 10
 65   IF(SP)66,66,67
 66   PRINT 1400, SP
      GO TO 10
 67   LQ=1
      TW=SQRTF(A/19.18)
      THETA=18.2*SP/(D*SQRTF(100.*T/D))
      SINH1=(2.71828**THETA-1./2.71828**THETA)/2.0
      COSH1=(2.71828**THETA+1./2.71828**THETA)/2.0
      GK=(SINH1-SINF(THETA))/(SINH1+SINF(THETA))
      GN=(COSH1-COSF(THETA))/(SINH1+SINF(THETA))
      THA2=THETA/2.
      SINH2=(2.71828**THA2-1./2.71828**THA2)/2.
      COSH2=(2.71828**THA2+1./2.71828**THA2)/2.
      GH=-(3.*SINH2*COSF(THA2)+COSH2*SINF(THA2))/(SINH1+SINF
     1(THETA))
      Q=-(SINH2*COSF(THA2)+COSH2*SINF(THA2))/(SINH1+SINF(THE
     1TA))
      GT=-(SINH2*COSF(THA2)-COSH2*SINF(THA2))/(SINH1+SINF(TH
```

```
      1ETA))
       BDA=((SP/D)**2/(T/D)**3)**0.25*SQRTF(SY/E)
       EPSL=(0.45*SY*D)/(E*T)
       B=TW*T/(A+TW*T)
       BETA=(11.*GN*T**2)/(SQRTF(100.*T/D)*(A+TW*T))
       BM=3.1416*D/(2.*CL)
       IBM=XFIXF(BM+0.5)
       BM=FLOATF(IBM)
       F=1.+2.*Q*(0.85-B)/(1.+BETA)
       X=1.+GH*(0.85-B)/(1.+BETA)
       Z=0.5+3.62*GT*(0.85-B)/(1.0+BETA)
       EL=1.57*SQRTF(D*T/2.)
       IF(EL-SP)80,80,70
70     EL=SP
80     ERTIA1=102.2*TW**4*(3.*EL*T/(EL*T+19.18*TW**2)*(0.125*
      1T/TW+1.43)**2+0.79)
       AB=A+TW*T
       C=(43.5*TW**3+(T*EL)*(8.0*TW+0.5*T))/(19.18*TW**2+EL*T)
       PCAM(L)=2.*T*SY/(D*(1.+GH*((0.85-B)/(1.+BETA)))*(1.+0.
      1148*((BDA**2-EPSL)**2)))
       NO=1
       P(NO)=PCAM(L)
       NO=NO+1
       PCW(L)=2.*T*SY/(D*SQRTF(F**2-F/2.+0.25))
       P(NO)=PCW(L)
       NO=NO+1
       PCL(L)=2.0*T*SY/(D*SQRTF(X**2-X*Z+Z*Z))
       P(NO)=PCL(L)
       NO=NO+1
       BN=2.
       PCB1(L)=2.*E*T*BM**4/(D*(BN**2+(.5*BM)**2-1.)*(BN**2+B
      1M**2)**2)+8.*(BN**2-1.)*E*ERTIA1/(D**3*SP)
       P(NO)=PCB1(L)
       NO=NO+1
       BN=3.
       PCB2(L)=2.*E*T*BM**4/(D*(BN**2+(.5*BM)**2-1.)*(BN**2+B
      1M**2)**2)+8.*(BN**2-1.)*E*ERTIA1/(D**3*SP)
       P(NO)=PCB2(L)
       NO=NO+1
       BN=4.
       PCB3(L)=2.*E*T*BM**4/(D*(BN**2+(.5*BM)**2-1.)*(BN**2+B
      1M**2)**2)+8.*(BN**2-1.)*E*ERTIA1/(D**3*SP)
       P(NO)=PCB3(L)
       BN=2.
       SMK1(L)=(PCD*(0.5*D+0.5*T)*TW/(AB*(1.0+BETA)))*(1.0+(0
      1.85*BETA)/B)
      2+E*C*(BN**2-1.0)*DELTA*PCD/((0.5*D)**2*(PCB1(L)-PCD))
       NO=1
       S(NO)=SMK1(L)
       NO=NO+1
       BN=3.
       SMK2(L)=(PCD*(0.5*D+0.5*T)*TW/(AB*(1.0+BETA)))*(1.0+(0
      1.85*BETA)/B)
      2+E*C*(BN**2-1.0)*DELTA*PCD/((0.5*D)**2*(PCB1(L)-PCD))
       S(NO)=SMK2(L)
```

```
      NO=NO+1
      BN=4.
      SMK3(L)=(PCD*(0.5*D+0.5*T)*TW/(AB*(1.0+BETA)))*(1.0+(0
     1.85*BETA)/B)
     2+E*C*(BN**2-1.0)*DELTA*PCD/((0.5*D)**2*(PCB1(L)-PCD))
      S(NO)=SMK3(L)
C     COMPUTE VOLUME OF MATERIAL IN ONE COMPARTMENT LENGTH
      V=0.7854*CL*((D+T/2.)**2-(D-T/2.)**2)+0.7854*((D-T/2.)
     1**2-(D-T/2.-
     25.93*TW)**2)*TW*FN+0.7854*FN*6.4*TW*((D-T/2.-5.93*TW)*
     3*2-(D-T/2.-8.0*TW)**2)
C     COMPUTE WEIGHT OF MATERIAL IN ONE COMPARTMENT LENGTH
      W(L)=V*DENS
      L=L+1
      GO TO (90,165),LP
 90   DO 110 N=1,6
      PDIFS(N)=PCD-P(N)
 110  CONTINUE
      PDIFCR=PDIFS(1)
      DO 120 N=2,6
      IF(PDIFS(N)-PDIFCR)120,100,100
 100  PDIFCR=PDIFS(N)
      NP=N
 120  CONTINUE
 122  IF(0.02*PCD-ABSF(PDIFCR))130,125,125
 125  LQ=LQ+1
 130  DO 140 N=1,3
      SDIFS(N)=SY-S(N)
 140  CONTINUE
      SDIFCR=SDIFS(1)
      DO 160 N=2,3
      IF(SDIFS(N)-SDIFCR)150,160,160
 150  SDIFCR=SDIFS(N)
      NQ=N
 160  CONTINUE
 162  IF(0.02*SY-ABSF(SDIFCR))164,163,163
 163  LQ=LQ+1
      GO TO (164,164,200),LQ
 164  LP=2
      PCRIT=PCD-PDIFCR
      SCRIT=SY-SDIFCR
 165  GO TO (170,180,190),LO
 170  AT=A
      A=0.96*A
      LO=2
      GO TO 60
 180  DELPE1=PCRIT-P(NP)
      DELS1=SCRIT-S(NQ)
      A=AT
      SPT=SP
      SP=1.04*SP
      LO=3
      GO TO 60
 190  DELPE2=PCRIT-P(NP)
      DELS2=SCRIT-S(NQ)
```

```
      SP=SPT
      DOT=DELS2-DELPE2*DELS1/DELPE1
      DOP=SDIFCR-PDIFCR*DELS1/DELPE1
      PRY=DOP/DOT
      PRX=(PDIFCR-PRY*DELPE2)/DELPE1
      A=(1.+0.04*PRX)*A
      SP=(1.-.04*PRY)*SP
      GO TO 15
200   PRINT 1000,A
      PRINT 1070,FN
      PRINT 1140,PCAM(L-1)
      PRINT 1150,PCW(L-1)
      PRINT 1160,PCL(L-1)
      PRINT 1170,PCB1(L-1)
      PRINT 1200,PCB2(L-1)
      PRINT 1210,PCB3(L-1)
      PRINT 1220,SMK1(L-1)
      PRINT 1230,SMK2(L-1)
      PRINT 1240,SMK3(L-1)
      PRINT 1100,SP
      PRINT 1110,T
      PRINT 1120,TW
      PRINT 1180,V
      PRINT 1190,W(L-1)
      PRINT 450,THETA
      PRINT 450,SINH1
      PRINT 450,COSH1
      PRINT 450,GK
      PRINT 450,GN
      PRINT 450,THA2
      PPINT 450,SINH2
      PRINT 450,COSH2
      PRINT 450,GH
      PRINT 450,Q
      PRINT 450,GT
      PRINT 450,BDA
      PRINT 450,EPSL
      PRINT 450,B
      PRINT 450,BETA
      PRINT 450,BM
      PRINT 450,F
      PRINT 450,X
      PRINT 450,Z
      PRINT 450,EL
      PRINT 450,ERTIA1
      PRINT 450,AB
      PRINT 450,C
      PRINT 1130, PCRIT
      PRINT 1130,SCRIT
      PRINT 1130,PDIFCR
      PRINT 1130, SDIFCR
      PRINT 1130, DELPE1
      PRINT 1130, DELPE2
      PRINT 1130, DELS1
      PRINT 1130, DELS2
```

```
      PRINT 1130, DOT
      PRINT 1130, DOP
      PRINT 1130, PRY
      PPINT 1130, PRX
      GO TO (210,220,250),LR
 210  WLEAST=W(L-1)
      PRINT 1370, WLEAST
      LR=2
      TR=T
      T=0.95*T
      GO TO 15
 220  IF(WLEAST-W(L-1))240,240,230
 230  WLEAST=W(L-1)
 240  PRINT 1370,WLEAST
      T=1.04*TR
      LR=3
      GO TO 15
 250  IF(WLEAST-W(L-1))270,270,260
 260  WLEAST=W(L-1)
      PRINT 1370, WLEAST
      T=1.04*T
      GO TO 15
 270  PRINT 1370,WLEAST
      GO TO 10
 450  FORMAT(F20.5)
1000 FORMAT(1H1,10HFRAME AREA,19X,1H=,F10.2,3X,7HSQ. IN.)
1010 FORMAT(1H1,14HYIELD STRENGTH,15X,1H=,F10.2,3X,6HP.S.I.)
1020 FORMAT(1X,14HYOUNGS MODULUS,12X,1H=,F13.2,3X,6HP.S.I.)
1030 FORMAT(1X,21HMEAN DIAMETER OF HULL,8X,1H=,F10.2,3X,6HI
                NCHES)
1040 FORMAT(1X,14HCOLLAPSE DEPTH,15X,1H=,F10.2,3X,4HFEET)
1050 FORMAT(1X,16HBULKHEAD SPACING,13X,1H=,F10.2,3X,6HINCHE
                S)
1070 FORMAT(1X,30HNO. FRAMES BETWEEN BULKHEADS =,F10.2,3X,6
                HFRAMES)
1060 FORMAT(1X,19HDENSITY OF MATERIAL,10X,1H=,F10.4,3X,16HL
                B. PER CU. I
    1NCH)
1080 FORMAT(1X,30HALLOWABLE OUT-OF-ROUNDNESS   =,F10.2,3X,6
                HINCHES)
1090 FORMAT(1X,30HPRESSURE AT COLLAPSE DEPTH   =,F10.2,3X,6
                HP.S.I.)
1100 FORMAT(1X,13HFRAME SPACING,16X,1H=,F10.2,3X,6HINCHES)
1110 FORMAT(1X,15HSHELL THICKNESS,14X,1H=,F10.2,3X,6HINCHES)
1120 FORMAT(1X,13HWEB THICKNESS,16X,1H=,F10.2,3X,6HINCHES)
1130 FORMAT(F20.5)
1140 FORMAT(1H0,30HCOLLAPSE7PRESS. FROM 92AMOD. =,F10.2,3X,
                6HP.S.I.)
1150 FORMAT(1X,30HCOLLAPSE PRESS. FROM WENK    =,F10.2,3X,6
                HP.S.I.)
1160 FORMAT(1X,30HCOLLAPSE PRESS FROM LUNCHICK =,F10.2,3X,6
                HP.S.I.)
1170 FORMAT(1X,30HCOLL PRESS FR BRYANT, 2 LOBES=,F10.2,3X,6
                HP.S.I.)
1180 FORMAT(1X,30HVOLUME OF ONE COMPT MATERIAL =,F10.2,3X,1
```

```
                    2HCUBIC INCH)
   1ES)
1190 FORMAT(1X,21HWEIGHT OF COMPARTMENT,8X,1H=,F10.2,1X,6HP
                    OUNDS)
1200 FORMAT(1X,30HCOLL PRESS FR BRYANT, 3 LOBES=,F10.2,3X,6
                    HP.S.I.)
1210 FORMAT(1X,30HCOLL PRESS FR BRYANT, 4 LOBES=,F10.2,3X,6
                    HP.S.I.)
1220 FORMAT(1X,30HMAX STR FR BUSHIPS,  2 LOBES =,F10.2,3X,6
                    HP.S.I.)
1230 FORMAT(1X,30HMAX STR FR BUSHIPS,  3 LOBES =,F10.2,3X,6
                    HP.S.I.)
1240 FORMAT(1X,30HMAX STR FR BUSHIPS,  4 LOBES =,F10.2,3X,6
                    HP.S.I.)
1340 FORMAT(F6.2,2F10.0,3F6.0,F6.4,F4.0,F4.2)
1370 FORMAT(1X,30HCOMPARTMENT OF LEAST WEIGHT  =,F10.2,3X,6
                    HPOUNDS)
1390 FORMAT(1X,30HACTION TERMINATED, NEGATIVE A=,F10.2,3X,7
                    HSQ. IN.)
1400 FORMAT(1X,30HACTION TERMINATED, NEGAT. SP =,F10.2,3X,6
                    HINCHES)
     END
```

NOTE

FORMAT STATEMENTS REQUIRE A CARD FORM 72 CHARACTERS IN WIDTH. IN ORDER TO FACILITATE A NARROWER PRINTOUT THOSE FORMAT STATEMENTS LONGER THAN 60 CHARACTERS WERE BROKEN AND THE EXTRA CHARACTERS PRINTED ON THE FOLLOWING LINE WITH AN EXAGERATED INDENTATION. A USER COPYING THE PROGRAM SHOULD TYPE, FOR EXAMPLE, LINE 1400 AND THE NEXT INDENTED LINE ON THE SAME CARD.

COMPUTER PROGRAM SYMBOLS

A	Cross-sectional area of a frame
AB	Cross-sectional area of a frame plus the area of shell under the web
AT	Same as A
B	Page 18
BDA	Lambda - Figure 4
BETA	Page 18
BM	m (see formula symbols)
BN	n (see formula symbols)
C	Formula 31
CD	Collapse depth
CL	Compartment Length
COSH1	COSH θ
COSH2	COSH $\theta/2$
D	Hull diameter
DELPE1	$P_{crit} - P_{crit}$ (after A is incremented)
DELPE2	$P_{crit} - P_{crit}$ (after SP is incremented)
DELS1	$S_{crit} - S_{crit}$ (after A is incremented)
DELS2	$S_{crit} - S_{crit}$ (after A is incremented)
DELTA	Allowable out-of-roundness of the hull
DENS	Density of construction material
DOT, DOP	Intermediate values in the solution of two differential equations
E	Young's modulus

EL	Effective length of shell plating
EPSL	ϵ, page 9
ERTIAL	Moment of inertia of a T section
F	Page 31
FN	No. of frames in one compartment length
GH	Figure 8
GK	Figure 8
GN	Figure 8
GT	Page 34
P	Predicted collapse pressure = PCAM, PCW, PCL, PCB1, PCB2, PCB3
PCAM	Predicted collapse pressure from modified formula 92A
PCB1	Predicted collapse pressure from Bryant's (Kendrick) formula (1st failure mode)
PCB2	(2nd failure mode)
PCB3	(3rd failure mode)
PCD	Pressure at collapse depth
PCL	Predicted collapse pressure from Lunchick
PCRIT	Lowest collapse pressure of the 6 predicted
PCW	Predicted collapse pressure from Wenk
PDIFCR	Highest of the 6 PDIFS values
PDIFS	= PCD - P (six of these calculated)
PRX	No. of increments by which SP must be changed in reaching an optimum solution
PRY	No. of increments by which A must be changed in reaching an optimum solution
Q	Page 31

S	Predicted stress = SMK1, SMK2, SMK3
SCRIT	Highest stress of the 3 predicted
SDIFCR	Lowest of the 3 SDIFS values
SDIFS	SY - S (three calculated)
SINH1	SINH θ
SINH2	SINH θ/2
SMK1	Predicted stress (2 lobe mode of failure)
SMK2	Predicted stress (3 lobe mode of failure)
SMK3	Predicted stress (4 lobe mode of failure
SP	Frame spacing
SPT	Same as SP
SY	Yield stress
T	Shell Thickness
THA2	θ/2
THETA	θ (Figure 8)
TW	Web thickness
V	Volume of material in shell and frames over one compartment length
W	Weight of material in shell and frames over one compartment length
WLEAST	Weight of the lightest compartment of those considered
X	Page 34
Z	Page 34

4. Output

a. Given the following inputs for a section of pressure hull:

1.) Diameter

2.) Length between transverse bulkheads

3.) Collapse depth

4.) Construction material

5.) Tolerance to which the construction material will be fabricated

the computer program produces recommended values for:

1.) Shell thickness

2.) Frame size, and

3.) Frame spacing.

With the above information, it is possible to compute displacement of the cylinder and weight of material used in construction of the hull. The computer program does, in fact, calculate weight of hull since it was decided that "least weight" would be the criterion for optimum design.

b. But the process of design involves more than one answer to one problem. Normally, a designer will study several vehicles with various characteristics and he will attempt to gather as much information as possible about each one. It is not enough to know that a computer program has recommended certain values for a certain vehicle. Each

of the recommended values must be checked for accuracy, logic, and applicability to the planned use and the construction methods currently available. There is always the possibility that a computer program will recommend as optimum a set of values impossible to adhere to in actual construction.

c. To aid a designer in comparing vehicles and to aid in analyzing the computer program itself, or possibly to help in studying the design parameters of submarine construction, the computer program listed in this section prints out a large number of values computed in the preliminary calculations as well as the final answers to the main problem. Once a user has gained familiarity with the program he will probably eliminate much of the printed output by withdrawing from the input deck those PRINT statements referring to the unnecessary values. He may also add some cards or some additional calculations which will help him in his design or analysis.

Referring to the sample output (page 60), the following values are printed out after each solution at a given thickness.

Computer Output

Page One

1. Yield strength of the material
2. Collapse depth
3. Pressure at collapse depth
4. Young's modulus
5. Hull diameter
6. Compartment length
7. Density of the material
8. Allowable out-of-roundness of the hull

Page Two

1. Frame Area

2. Number of frames

3-8. Critical pressure predicted by formula 92a-modified, Wenk, Lunchick, and three modes by Bryant

9-11. Three values of yield strength predicted by the formula in section 1-c-6 of this appendix.

12. Frame spacing

13. Shell thickness

14. Web thickness

15. Volume of material in the shell and frames

16. Weight of material in the shell and frames

17-38. Preliminary calculation values beginning with "THETA" and ending with "C" as listed on the fourth page of the computer program.

39-50. Values used in the solution of the two differential equations when determining the required changes.

51. "Least weight" of those compartments considered.

d. Since thickness is first decreased to 95% of the predicted value and then increased to 104% of that predicted by the hoop stress formula, the values on page two will be printed at least three times. If, as may happen in some cases, the solution with thickness increased produces the "least weight" solution, thickness will continue to be increased by increments of 4% until a "least weight" solution is reached and passed. (Each of these incremented solutions will also require one page of printed output.) This series of events would occur if, by increasing thickness, frame size and the number of frames could be decreased enough to achieve an overall reduction in weight. After a certain number of thickness increases, however, weight will begin to increase at which time the program will terminate. Experience indicates, however, that the "least weight" solution will occur when "T" is reduced to 95% of the thickness predicted by the hoop stress formula, and if the hoop stress prediction is ignored, "least weight" will occur at about 70% of the predicted thickness.

```
YIELC STRENGTH                    =  55500.00   P.S.I.
CCLLAPSE DEPTH                    =   1530.00   FEET
PRESSURE AT CCLLAPSE DEPTH        =    680.00   P.S.I.
YCUNGS MCDULUS                 = 30000000.00   P.S.I.
MEAN DIAMETER CF HULL             =    214.70   INCHES
BULKHEAD SPACING                  =    416.00   INCHES
DENSITY CF MATERIAL               =     .2840   LB. PER CU. INCH
ALLOWABLE CUT-CF-RCUNDNESS        =       .50   INCHES
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FRAME AREA                          =      8.26   SQ. IN.
NC. FRAMES BETWEEN BULKHEADS        =     19.56   FRAMES

CCLLAPSE7PRESS. FROM 92AMCD.        = 7[illegible].[illegible]2   P.S.I.
COLLAPSE PRESS. FROM WENK           =    853.14   P.S.I.
CCLLAPSE PRESS FROM LUNCHICK        =    791.74   P.S.I.
CCLL PRESS FR BRYANT, 2 LCBES=         4723.31   P.S.I.
CCLL PRESS FR BRYANT, 3 LOBES=         1558.19   P.S.I.
CCLL PRESS FR BRYANT, 4 LCBES=         2207.23   P.S.I.
MAX STR FR BUSHIPS,  2 LCBES =        41390.50   P.S.I.
MAX STR FR BUSHIPS,  3 LCBES =        46662.06   P.S.I.
MAX STR FR BUSHIPS,  4 LOBES =        54042.24   P.S.I.
FRAME SPACING                       =     22.41   INCHES
SHELL THICKNESS                     =      1.25   INCHES
WEB THICKNESS                       =       .66   INCHES
VCLUME CF ONE COMPT MATERIAL        = 228702.30   CUBIC INCHES
WEIGHT CF COMPARTMENT               =  64951.45   POUNDS
             2.49059
             5.99276
             6.07562
              .81633
             1.04127
             1.24530
             1.59335
             1.88091
            -.50168
            -.34727
              .19287
              .65292
              .14018
              .09028
             2.58025
             1.00000
              .85262
              .89355
              .64815
            18.18325
           131.12429
             9.08498
             4.70594
           663.14374
         55986.18652
            -6.42158
           347.75732
             1.38360
             7.50674
          -219.65967
           -87.05908
          1104.70824
          3239.03876
             2.93203
             6.10457
CCMPARTMENT CF LEAST WEIGHT         =  63257.29   POUNDS
```